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Gamma Polari-Calorimetry with SOI pixels for proposals at Extreme Light Infrastructure (ELI-NP)

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ON BEHALF OF RA5 AT ELI-NP

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We introduce the concept of Gamma Polari-Calorimetry (GPC) dedicated for proposals at Extreme Light Infrastructure in the Romanian site (ELI-NP). A simulation study shows that an assembly of thin SOI pixel sensors can satisfy our requirements to GPC.

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1 Introduction

From a field theoretical point of view, high energy density states created in the vacuum are interesting objects to be studied. If the energy density is high enough, particles and anti-particles are created by converting the energy into particle masses and momenta. In order to understand such particle production mechanisms from intense fields, the perturbative treatment of elemental interactions by expanding with weak coupling strengths is inappropriate, instead, the nonperturbative approach by expanding with field strengths is rather important. So far such high energy density states in the vacuum are realized only in point-like or quasi-point-like spots by colliding high energy charged particles where produced systems are maintained only for an instant and rapidly evolve into dynamically complicated final states. This makes comparisons between theoretical predictions and experimental data difficult. In this respect, elemental dynamics in strong fields in the vacuum are not quantitatively understood yet. High-intensity laser fields, on the other hand, can produce relatively static high energy density states with controlled polarization states where spontaneous e^+e^- pair creations are expected. Moreover, a high field laser also simply implies that we can use a large number of laser photons or high luminosity of photon beams. This allows us to search for undiscovered low-mass fields weakly coupling to photons which could be relevant to dark components of the Universe [1, 2, 3, 4].

The pair creation threshold is known as the Schwinger critical field [5] $E_s = \frac{m^2 c^3}{e\hbar} = 1.3 \times 10^{18} \text{V/m}$ corresponding laser intensity of $4 \times 10^{29} \text{W/cm}^2$. An electric field E causes the pair creation via the tunneling effect in the vacuum. The rate of the pair creation in the electric field E is proportional to the following tunneling factor $\exp\{-\pi E_s/E\}$. This corresponds to the non-perturbative description of the phenomenon.

The leap of high intensity lasers as a function of year is illustrated in Fig.1. As one of cutting-edge projects, Extreme Light Infrastructure (ELI) [6] is approved by European Union which has been eventually divided into three sites: ELI-Beamlines facility in Czech Republic, ELI-Attosecond facility in Hungary and ELI-Nuclear Physics facility (ELI-NP) in Romania. In particular, the ELI-NP site is a unique laser facility where two 10 PW (220 J / 22fs) lasers operated every 60 sec and also a 700 MeV electron beam from a linac are simultaneously available within the same experimental area [7]. With a 10 PW field, we may be able to achieve 10^{22-24}W/cm^2 depending on the achievable spot size of the focused beam. This is still far from E_s . Because of the strong exponential suppression, we do not expect for tunneling pair creations to occur with a reasonable event rate in the laboratory. However, if high-intensity lasers could be combined with energetic photons or electrons, we can effectively lower the tunneling probability for the pair creation from the laser induced vacuum. The production rate $R_{e^+e^-}$ is evaluated as $R_{e^+e^-} = \frac{e^2 E_l^2}{4\pi^3} \exp\{-\frac{8}{3} \frac{E_s}{E_l} \frac{m_e c^2}{\hbar\omega_\gamma}\}$ where E_l is the electric field of laser and $\hbar\omega_\gamma$ is the incident γ -ray energy [8].

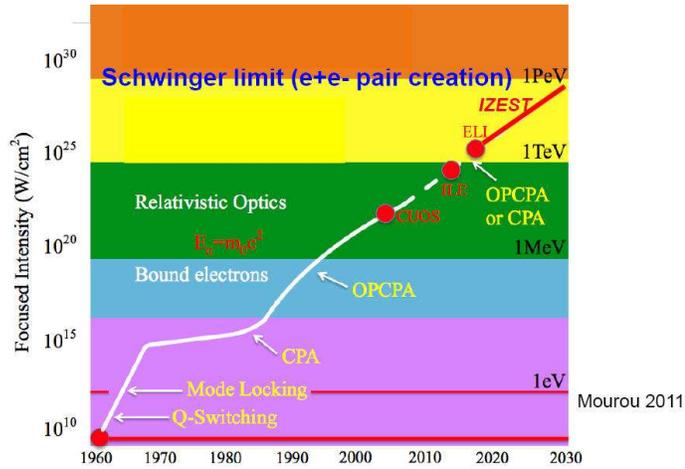


Figure 1: The leap of laser intensity as a function of year[9].

How can we prepare the high energy electron probe first ? We expect that a high-intensity laser can be used to generate electrons based on the Laser-Plasma-Accelerator technology. Recently 4.2 GeV electron acceleration is demonstrated with 0.3 PW [10] and actually it is planned to be extended beyond 10 GeV at the ELI-Beamlines facility. If we can use a multi-GeV electron beam, we also can produce high energy γ -rays via Compton scattering between high energy electrons and a high-intensity laser field. Especially in the nonlinear Compton regime, more energetic γ -rays can be produced due to multi-photon absorption processes compared to that of the linear Compton scattering. However, in 10 PW class lasers, the nonlinear Compton process itself is subject to be verified. Therefore, the measurement of the degree of linear polarization as well as scattered photon and electron energies will be important by itself and also for later applications as a secondary γ -ray source.

Even before reaching the real pair creation threshold, we can discuss the nonperturbative aspect of interactions between a probe photon and a high-intensity field by measuring so-called vacuum birefringence where refractive index of the vacuum under a high-intensity laser field depends on the polarization direction of probe photons [11]. With the ELI-NP parameter, the achievable refractive index change from that of the vacuum is only on order of 10^{-9} , therefore, it is extremely difficult to probe it with the optical wave length. Although such difficulty might be compensated by high statistics of probe laser photons per shot as discussed in [11], as an alternative probe, we may consider to utilize polarized γ -rays to enhance the phase shift with a much shorter wave length. For this purpose, we have to be able to measure the degree of linear polarization of incident probe γ -rays.

Given these purposes and environments at ELI, it is indispensable to develop a detection system which allows us to measure the degree of linear polarization of

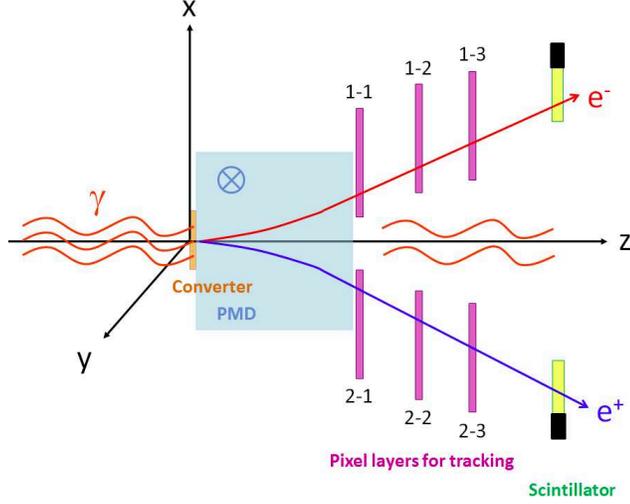


Figure 2: Schematic view of Gamma Polari-Calorimeter (GPC).

produced γ -rays as well as their energies simultaneously. This is the motivation for us to develop Gamma Polari-Calorimeter (GPC).

2 Gamma Polari-Calorimeter (GPC)

Requirements to GPC are

- 1) measurability of polarization from 0.1 GeV to a few GeV,
- 2) charge separations between electrons and positrons with momentum resolution below 20 MeV,
- 3) resolvable multiple γ -ray incidence up to order of ten γ -rays,
- 4) compact enough to make the detection system movable,
- 5) readout speed of 10 Hz at most.

Special conditions at ELI-NP are

- I)** γ -rays are generated from a laser focal spot within a cone angle of sub-mrad,
- II)** order of 10^4 γ -rays around 1 GeV are injected per shot.

Due to the energy range required in 1), we can utilize the photon conversion process within a thin foil in front of a uniform dipole magnetic field as illustrated in Fig.2. Since e^+e^- pairs are created within the foil, we can measure the momenta of the created pairs, equivalently, energies of incident γ -rays and also anisotropy of angles of reaction planes including generated pairs with respect to the linear polarization plane of incident γ -rays. Thus requirements 1) and 2) are satisfied with the conversion-based design. Because multiple scatterings within the foil dominantly degrades the angular resolution as well as momentum resolution, the thickness of the foil should be kept as thin as possible. On the other hand, the thickness also changes the conversion rate. By assuming II), the thickness of high-Z foil is most likely to be $20 \mu\text{m}$ with Au atoms in order to satisfy the requirement 3). Due to the special condition I), the conversion vertex point is well localized within a typical pixel size. Therefore, the accuracy of the track reconstruction is essentially determined by the pixel resolution of the first layer sensor and uniformity of the dipole magnetic field. We plan to introduce a compact Halbach-type permanent-magnet-based dipole in order to satisfy the requirement 4). The thickness of a pixel sensor layer is also important to avoid further increase of the number of multiple scatterings in order to allow accurate extrapolations of straight tracks to the first layer hit points. A square shaped sensor element is preferable compared to a rectangular shaped element like a strip-type sensor for the measurement of anisotropy of the reaction plane, because it makes analysis simpler without increasing the total thickness. Finally the requirement 5) is achievable if we assume to use a set of INTPX4 SOI sensor chips and the readout system [12].

3 Conclusion

We performed Geant4-based simulation by assuming available INTPIX4 SOI sensor chip with the pixel size of $17 \times 17 \mu\text{m}^2$ with geometry in Fig.3. The obtained momentum resolution to electron or positron tracks above 0.2 GeV is at a 7% level and the analyzing power of the polarimeter is about 50%. We thus conclude that the INTPIX4-based sensor assembly can surely perform polarimetry and calorimetry with required resolutions at the ELI-NP proposals.

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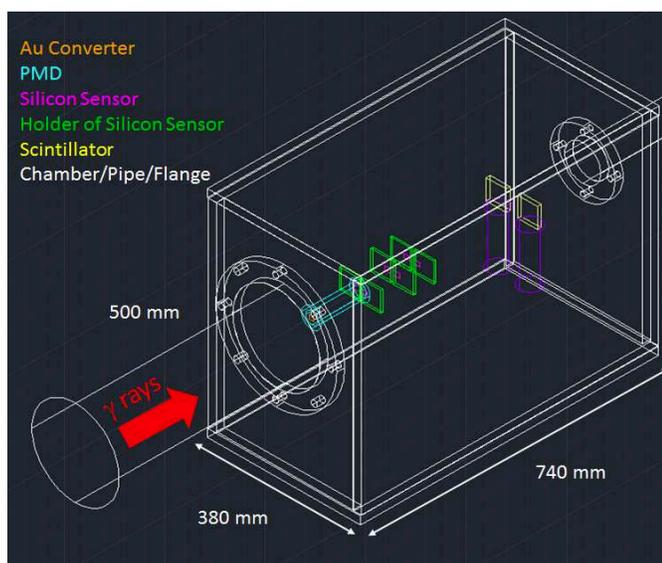


Figure 3: A present design of Gamma Polari-Calorimeter (GPC).

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